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Instabilities and Wave Dynamics in Magnetized Weakly Coupled Dusty Plasmas with Ionization and Recombination Effects

A Synopsis

Submitted in

Partial fulfillment for the degree of

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DECLARATION

I. I, **Manish Kumar Paliwal** hereby declare that all the statement made in this application are true, complete and correct to the best of my knowledge and belief and in the event of any information being found false or incorrect or any ineligibility being detected before or after the registration for Ph.D. My candidature is liable to be cancelled and legal action may be initiated against me.

II. I have deposited the required fee, as notified by the University regularly.

III. I have noted that if my application is found incomplete / defective, the same is liable to be rejected summarily and no correspondence will be entertained in this regard.

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Introduction: -

Dusty plasma refers to the state when a significant concentration of dust particles exists inside the plasma, resulting in collective interactions between the dust and the plasma. This contrasts with conditions when just a limited number of dust grains are present in the plasma, resulting in negligible impacts on the plasma. The condition characterized by a limited number of isolated particles inside a plasma is sometimes termed 'dust in plasma'. The dust is impacted by the plasma, which serves as its charge source, and the dynamics of the particles are affected by the plasma; nevertheless, in this context, the impact of the dust on the plasma is minimal. The term'dusty plasma' denotes that the plasma influences the dust, which then impacts the plasma. The plasma modifies the dust by imparting charge, resulting in a significant depletion of plasma electrons. In astrophysical settings, the presence of charged dust may influence plasma conductivity, therefore impacting the magnetic fields created by plasma currents**[1]**.When a plasma flow is examined in one-dimensional space, denoted as x. Dusty plasmas have three components: ions, electrons and dust grains.

The fundamental equations in dimensionless form that control the dusty plasmas for this system are:

$$\partial n_d \partial t + \partial \partial x(n_d u_d) = 0$$

$$\partial n_d \partial t + u_d \partial u_d \partial x + \sigma n_d \partial p_d \partial x = Z_d \partial \varphi \partial x$$

$$\partial p_d \partial t + u_d \partial p_d \partial x + \gamma \mathrm{p}_d \partial \mathrm{u}_d \partial \mathrm{x} = 0$$

$$\partial^2 \varphi \partial x^2 = \mathrm{Z}_d \mathrm{n}_d + \mathrm{n}_e - \mathrm{n}_\mathrm{i}$$

where, n_i (number density of ions) and the n_e (number density of electrons) satisfy Boltzmann distribution.

$$n_i = \mu e^{-s\varphi}$$

$$\mathrm{n}_e = \upsilon \mathrm{e}^{\beta \mathrm{s} \varphi}$$

where, Z_d is the number charge residing on the dust grain, which can be written as,

$$Z_d = 1 + \gamma_1 \varphi + \gamma_2 \varphi^2$$

where, n_d, u_d, p_d, φ are the number density, velocity, pressure of the hot dust and the electrical potential respectively **[2]**.

A dust particle inside a plasma acquires an electric charge and reacts to electric forces. The charge may vary from 0 to several hundred thousand electron charges, contingent upon the particle size and plasma conditions. It originates from the accumulation of electrons and ions from the plasma, and sometimes from the emission of electrons. In a plasma when emission processes are negligible, the equilibrium charge is negative due to the comparatively strong flux of electrons to an uncharged surface compared to that of ions. Conversely, when electron emission is substantial, the equilibrium charge is positive**[3]**.The primary concern in addressing dusty plasmas is to comprehend the mechanism by which particles acquire charge. Three fundamental processes must be taken into account:

(1) absorption of electrons and ions from the plasma,
(2) secondary emission, and
(3) ultraviolet-induced photoelectron emission.

Each operation may be shown as a flux or current to the particle, and given that the dust is electrically neutral, the cumulative current from all activities must equal zero, or

$$\sum I = I_e + I_i + I_{\text{sec}} + I_{pe} = 0$$

where the distinct terms denote the contributions from electrons, ions, secondary particles, and photoelectrons, respectively.

Photoelectron emission significantly affects dust particles in intense UV environment;however, it is often negligible in laboratory plasmas. Likewise, secondary emission is often insignificant in low-temperature plasmas. In these circumstances, an isolated particle inside a conventional low-temperature laboratory plasma would attain a negative surface potential, $V_s$in relation to the plasma due to the enhanced mobility of the electrons. V_s is ascertained by the equilibrium of electron and ion currents, $I_e + I_i = 0$. The electron current is defined as,

$$I_e = -4\pi a^2 e n_e \left(\frac{kT_e}{m_e}\right)^{1/2} exp\left(\frac{eV_s}{kT_e}\right)$$

where a represents the particle radius, T_e denotes the electron temperature, n_e indicates the electron density, and m_e signifies the electron mass. The orbital motion limited (OML) model is often used for the ion current to the particle:

$$I_i = 4\pi a^2 e n_i \left(\frac{kT_i}{m_i}\right)^{1/2} \left(1 - \frac{eV_s}{kT_i}\right)$$

where T_i is the ion temperature, n_i is the ion density, and m_i is the ion mass. The OML model is applicable in the regime when the particle radius is negligible relative to the Debye length**[4]**.When dust grains are 'closely packed' to the extent that the Debye sheaths of individual grains overlap, the charge of the particles diminishes**[5]**.

Dust particles inside a standard electron/positive ion plasma will get a negative charge owing to the preferred accumulation of the more mobile electrons**[6, 7]**.The dust grain acquires a negative charge compared to the plasma, resulting in the repulsion of electrons and the attraction of positive ions to the particles. The floating potential of the dust particle is determined by the equilibrium of collected electron and ion currents. If energetic electrons exist in the plasma, the implications of secondary emission may also need to be considered**[8]**. Photoelectric emission from dust under ultraviolet light may lead to the dust

obtaining a positive charge**[9]**.The charging of dust in space and astrophysical settings is mostly governed by photoelectron emission.

A compelling domain of contemporary research is the examination of electrostatic and electromagnetic waves in dusty plasmas. The theoretical existence of a wave known as dust acoustic waves (DAW) was predicted by Rao et al. (1990)**[10]**.This wave is a low-frequency acoustic wave. Chu et al. (1994) have previously conducted experimental verification of the presence of these waves **[11]**.Furthermore, Shukla and coworkers (1992) have theoretically predicted the occurrence of dust-ion acoustic waves**[12]**.Numerous experimental and theoretical investigations have been conducted on linear waves and their related instabilities in an unmagnetized dusty plasma. However, the majority of dusty plasmas in laboratory and space conditions are typically restricted by an external magnetic field. It is thus of practical significance to investigate many characteristics of dusty plasma waves in a magnetoplasma**[13-18]**.

Recent work shows significant interest in low-temperature plasmas that, with electrons and ions, include finite-sized highly charged particulate matter. This interest is driven by the common presence of such plasmas in extraterrestrial habitats, astrophysical contexts, and laboratory settings. Dust particles possess far more mass than ions and serve as a source of ionization and recombination for electrons. Wave propagation in dusty plasmas is anticipated to vary significantly from that in conventional two-component plasmas, and the presence of charged dust may markedly affect the properties of typical plasma wave modes. The inclusion of statically charged dust grains alters the current plasma wave spectrum. Moreover, dust dynamics provides novel eigenmodes, including dust-acoustic mode, dust-lattice mode, and dust Bernstein–Greene–Kruskal modes. Dust particles included in plasma experience several forces. The electric force is presumably a direct result of the charging of the dust

particles. The electric force primarily governs the confinement of negatively charged particles inside the positive plasma potential. Recently, the impact of the polarization force on dusty plasma processes has also been highlighted. The polarization force arises from the distortion of the Debye sheath surrounding the particles inside nonuniform plasmas**[19]**.It is given by,

$$\mathbf{F}_p = -q_d^2 \nabla \lambda_D / 2\lambda_D^2$$

where,$q_d = -eZ_d, \lambda_D = \lambda_{Di}/\sqrt{1 + (\lambda_{Di}/\lambda_{De})^2}$is the linearized Debye length, with$\lambda_{Di(e)} = \sqrt{\varepsilon_0 k_B T_{i(e)}/n_{i(e)}e^2}$represents the ion (electron) Debye length, T_j=i_e denotes the temperatures in energy units, and n_j=i_e signifies the number densities. Recent theoretical research has concentrated on the impact of the polarization force on various collective phenomena in dusty plasmas.Charged dust in a plasma affects collective behavior in two ways. The excitation and propagation features of conventional wave modes are altered even at frequencies where particles do not directly engage in the wave motion. This arises from the influence on the plasma quasineutrality requirement, which for negatively charged particles is

$$n_i = n_e + Z_d n_d$$

Hence, Z_j = Qj/e and n_a denotes the density of dust particles. Secondly, new extremely low frequency (few Hz) modes emerge in which the dust particles engage in the wave dynamics. The dust particles may be visualised, allowing for the visual observation and recording of the features of these “dust modes” on tape.

Waves in dusty plasmas have several parallels to those in plasmas containing negative ions, but with significant distinctions. The charge on a dusty plasma is not inherently constant. The charge varies with the disparity between the particle and plasma potential; hence, it will oscillate in accordance with changes

in the plasma potential. A distinctive characteristic of dusty plasma is the potential for a broad range of dust sizes, leading to a variation in particle masses and charges. Theoretical research on dusty plasmas characterized by extensive size distributions is now in its nascent phase.Verheest provided a summary of theoretical research on waves in dusty plasmas, focusing specifically on space plasmas**[20]**.The most straightforward method for comprehending wave events in dusty plasmas is to use the fluid equations, considering the dust as an additional fluid component. D'Angelo used this methodology in 1990 to derive a dispersion relation for low-frequency electrostatic waves in a magnetized dusty plasma**[21]**.Building upon this foundational approach, the present research examines wave dynamics and instabilities in magnetized, weakly coupled dusty plasmas, integrating ionization and recombination processes within this framework.

Review of Literature: -

This review aims to synthesize and critically assess the current research on wave dynamics and instabilities in magnetized dusty plasmas. This review highlights advancements in the investigation of dusty plasma.

Varma and Shukla (1995) discovered that a nonuniform dusty plasma, maintained in equilibrium inside a magnetic field against gravitational forces, has a polarization electric field E_0 directed towards gravity for negatively charged dust grains. The $E_0 \times B_0$ drift of plasma carrying a positive current, in conjunction with compressible dust dynamics, causes a new flute-like exchange instability distinct from the conventional Rayleigh-Taylor mode**[22]**.

Astrophysical dust is present in several environments, including interstellar and circumstellar media, as well as in the vicinity of planets and comets. Common sighting throughout the Solar System includes planetary rings, asteroid belts, cometary comae and tails, as well as areas of Earth's lower magnetosphere.

Dust particles inside surrounding plasmas acquire electrical charge via many mechanisms and interact with electromagnetic fields. In the 1980s, Voyager cameras spotted intriguing phenomena ascribed to charged dust, including radial spokes in Saturn's B-ring and braiding in its F-ring. Collective effects are significant when the inter-grain distance of dust is less than the plasma Debye length, originating from discoveries that micron-sized dust grains may possess substantial negative charges and correspondingly greater masses. The characteristic dust frequencies are far lower than the equivalent electron or ion amounts, resulting in novel low-frequency eigenmodes that may account for some low-frequency noise in space and astrophysical plasmas. Electrostatic repulsion among charged dust grains inhibits the collapse of planetary rings into thin sheets, whereas oscillations in the transverse thickness of the rings lead to resonant events, which are accountable for the gaps seen in the rings of Jupiter and Saturn. Additional characteristics are associated with variable dust charges, which need complex source and/or sink terms in the description, subsequently resulting in novel electrostatic and electromagnetic instabilities. Verheest (1996) examined several studies addressing waves and instabilities in dusty space plasmas, including both constant and variable dust charges, at linear and nonlinear levels, including double layers, solitons, vortices, and other wave phenomena**[23]**.

Merlino et al. (1998) detailed theoretical and practical investigations of low-frequency electrostatic waves in plasmas with negatively charged dust particles. Charged dust alters the characteristics of ion-acoustic waves and electrostatic ion-cyclotron waves via the quasi-neutrality condition, despite the dust grains not engaging in the wave dynamics. Incorporating dust dynamics into the study reveals the emergence of novel 'dust modes'—specifically, dust acoustic and dust cyclotron modes. The results of laboratory investigations concerning dust ion acoustic (DIA) waves and electrostatic dust ion cyclotron (EDIC) waves

were also presented in this study. These modes are more readily stimulated in a plasma containing negatively charged particulates. Observations of dust acoustic (DA) waves were reported, and the measurements of the dispersion relation were compared with those derived from fluid theory**[24]**.

D'Angelo (2000) encapsulated the experimental and theoretical research on waves and instabilities in dusty plasmas conducted by the University of Iowa group during the preceding decade. The research mostly advanced along two concurrent trajectories, examining identical wave modes and instabilities in both dusty plasmas and plasmas containing significant proportions of negative ions. Given that dust grains in ordinary laboratory dusty plasmas are negatively charged, the inherent relationship between wave phenomena in these plasmas and those in negative ion plasmas is unsurprising. The work further investigated the impact of negatively charged dust grains on ionization instability in low-ionization plasmas, where electrons possess energy marginally above the ionization energy of the neutral gas**[25]**.

D'Angelo (2003) provided a comprehensive analysis of Hall instabilities in collisional dusty plasmas, using fluid equations for all charged constituents. Two modes are often feasible: one with frequencies in the ion-acoustic spectrum (the Farley–Buneman mode) and the other with frequencies in the dust-acoustic spectrum. Calculations were conducted for laboratory-type plasmas and ionospheric-type plasmas. The real and imaginary components of the mode frequencies were derived as functions of the electric field, which is perpendicular to the magnetic field, B, that permeates the plasma**[26].**

Brodin et al. (2009) examined a dusty plasma in which dust particles had a magnetic dipole moment. A Hall-MHD model, adapted to include intrinsic magnetization, was formulated. The model demonstrated energy conservation, and the energy density and flow were calculated. The general dispersion relation was obtained, demonstrating that kinetic dust-Alfvén waves become unstable

under conditions of low dust and ion temperatures coupled with high dust density**[27].**

Rogue waves—rare, unpredictable localized phenomena with significant amplitudes—have been experimentally documented in several nonlinear wave occurrences, including water waves, optical waves, second sound in superfluid He II, and ion acoustic waves in plasmas. Previous research has mostly concentrated on one-dimensional (1D) wave phenomena via modulation instabilities, with comparatively little emphasis on higher-dimensional dynamics. The existence of rogue waves in nonlinear 3D acoustic-type plasma waves, the kinetic mechanisms behind their generation, and their relationship with adjacent 3D waveforms remain unexamined basic questions. Tsai et al. (2016) documented the direct experimental observation of dust acoustic rogue waves in dusty plasmas and illustrated a model of three-dimensional particle focusing influenced by the surrounding tilted and ruptured wave crests, which correlates with an increased likelihood of low-amplitude holes for rogue-wave creation**[28].**

Grimalsky et al. (2017) examined the nonlinear dynamics of the dusty plasma–dusty beam instability inside dusty plasma waveguides constrained by dielectrics. The dusty plasma has positive ions as the lighter component and negative dust as the heavier component. A stream of dust particles traverses the waveguide. The hydrodynamic equations for dust and beam particles, namely the continuity equations, momentum equations, and the Poisson equation, were used. The Boltzmann distribution is applicable to ions. The electric and hydrodynamic boundary conditions were implemented at the interfaces. The simulations showed that the dusty sound waves of low amplitudes are vulnerable to significant amplification owing to convective instability, even when the concentration of beam particles is ≤ 0.1 of the uniform dust concentration. The amplification swiftly transitions to a domain of pronounced

surface nonlinearity, and at the interfaces, the fluctuations in dust concentration reach very high levels, resulting in the collapse of the beam's dust component**[29].**

Bukhari et al. (2018) examined novel characteristics of twisted dusty plasma modes and their related instabilities in penetrating plasmas. A generalized dispersion relation was derived from the Vlasov–Poisson model equations for a Maxwellian distributed plasma to examine dust-acoustic and dust-ion-acoustic waves with limited orbital angular momentum (OAM) states. The criteria for existence of damping and growth rates were examined, revealing substantial alterations in twisted dusty modes relative to straight propagating dusty modes. The increasing rate of instability, influenced by particle streaming and twist effects in the wave potential, is substantially altered by Laguerre–Gaussian profiles. The study's relevance to wave excitations resulting from the infiltration of solar wind into cometary clouds or interstellar dusty plasmas was examined**[30].**

Sharma et al. (2021) examined the dynamical characteristics of dust-ion-acoustic waves (DIAWs) in a collisional non-extensive dusty plasma consisting of mobile ions, q-nonextensive electrons, and stationary dust grains, with few collisions between dust and ions. The reductive perturbation method (RPT) was used to derive the damped Korteweg-de Vries (DKdV) equation. In the absence of collisions between dust and ions, the damping component disappears, and the DKdV equation simplifies to the KdV equation. An examination of bifurcation in the dynamical system derived from the KdV equation was conducted. Analytical solitary wave solutions and numerical periodic wave solutions of the KdV equation were provided. Approximate analytical solutions for the DKdV problem were provided utilizing the innovative (G'/G)-expansion method. Consequently, new approximate analytical solutions of DIAWs were derived for the DKdV equation**[31].**

Pahuja et al. (2025) elucidated the theoretical framework for the nonlinear scattering of an electromagnetic ion cyclotron (EMIC) wave into an ion acoustic wave (IAW) and a scattered ion-cyclotron wave (SICW) in a dusty plasma using fluid theory. The low-frequency nonlinearity originates from the parallel ponderomotive force acting on ions, whereas the high-frequency nonlinearity results from the nonlinear current density of ions. A nonlinear dispersion relation was derived for the coupled modes. A formula for the SICW growth rate wasestablished. The calculation of the turbulence growth rate considers the usual characteristics of dusty plasma. An elevated growth rate was seen with an increase in both the pump wave amplitude and the number density (n_0 in cm^{-3}) of dust grains. Nonetheless, a reduction in the growth rate was seen with increasing relative density $d=n_{0i}/n_{0e}$ of dust particles, magnetic field strength, and the size of the dust grains. Consequently, these wave modes had many uses in space, astrophysics, and laboratory investigations**[32].**

Research Aims and Objectives: -

The current study has following objectives:

- Numerical investigation of instabilities in a magnetized weakly coupled plasma with dominant ionization over recombination.
- Computational analysis of instability dynamics in a magnetized weakly coupled plasma with predominant recombination over ionization.

Research Methodology & Materials: -

The present study undertakes a comprehensive numerical investigation of plasma instabilities and wave dynamics in a magnetized, weakly coupled dusty plasma system influenced by both ionization and recombination processes. The plasma model considered will consist of electrons, ions, and negatively charged dust particles, where the dust component is assumed to be weakly coupled due to relatively lower interparticle interaction strength compared to thermal energy.

The study will be primarily aimed at understanding the distinct instability behaviors arising in two regimes: one where ionization dominates over recombination, and the other where recombination effects are more pronounced than ionization. A static external magnetic field will be applied at an arbitrary oblique angle to the direction of wave propagation, allowing the study of anisotropic influences on the plasma behavior and wave dynamics.

A linear perturbation method will be employed to analyze the development of instabilities. Small perturbations will be introduced to the equilibrium plasma parameters, and the governing equations will be linearized to derive a general dispersion relation. This dispersion relation will be then solved numerically using computational tools such as MATLAB. A detailed parametric analysis will be conducted to investigate how various factors—including ionization and recombination rates, magnetic field strength, propagation angle, dust particle charge, and plasma density—affect the instability growth rates and wave propagation characteristics. Two distinct scenarios will be considered: one in which the plasma experiences dominant ionization and another where recombination effects prevail.

Tentative Chapterization: -

Chapter 1 – Introduction

This chapter will introduce dusty plasmas, highlighting their importance in fields like space physics and astrophysics. It will also discuss ionization and recombination along with wave dynamics and instabilities in plasmas.

Chapter 2 - Review of Literature

This chapter will review existing studies on dusty plasmas, particularly in the presence of magnetic fields.

Chapter 3 –Research Methodology

This chapter will describe the mathematical models used for analysing wave dynamics and instabilities in dusty plasmas. It will also incorporate details regarding numerical simulations and analytical techniques used to solve dispersion relations and examine plasma instability.

Chapter 4 – Result and Discussion

This chapter will present the findings on wave dynamics, instability conditions and the impact of ionization and recombination.

Chapter 5 – Conclusion and Future Scope

This chapter will provide conclusion of the study. It will also outline the scope for future research.

Expected outcome of the proposed work: -

The proposed work is expected to yield a comprehensive understanding of the behaviour and evolution of instabilities in magnetized weakly coupled dusty plasmas under varying ionization and recombination conditions. In the case where ionization dominates over recombination, the study anticipates identifying enhanced instability growth rates and altered wave structures due to increased particle generation. Conversely, when recombination is predominant, a suppression or modulation of instabilities is expected, along with changes in the plasma equilibrium and wave propagation characteristics. The numerical and computational analyses will help delineate the critical parameters influencing instability thresholds.

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Signature of the Supervisor/Guide **Signature of the Candidate**

(Seal of the Supervisor with University Name)